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Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types

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Abstract

Gasification biochar (GB) contains recalcitrant carbon that can contribute to soil carbon sequestration and soil quality improvement. However, the impact of GB on plant-available water capacity (AWC) and plant growth in diverse soil types still needs to be explored.

A pot experiment with spring barley (*Hordeum vulgare* L.) was conducted to investigate the effect of soil amendment by 1 % straw and wood gasification biochar (SGB and WGB), respectively, on AWC and plant growth responses under two levels of water supply in a temperate sandy loam and a coarse sandy subsoil. In the sandy loam, the reduced water regime significantly affected plant growth and water consumption, whereas the effect was less pronounced in the coarse sand. Irrespective of the soil type, both GBs increased AWC by 17-42%, with the highest absolute effect in the coarse sand. The addition of SGB to coarse sand led to a substantial increase in plant biomass under both water regimes: shoot growth by 40-165% and root growth by 50-57%. However, no positive effects were achieved by the addition of WGB. In the sandy loam, soil application of GB had no or negative effects on plant growth.

Our results suggest that SGB has considerable potential for enhancing crop productivity in coarse sandy soils by increasing soil water retention and improving root development.

Keywords:

Gasification biochar; Available water capacity; Coarse sand; Barley; Shoot and root growth; Soil structure

Abbreviations

GB	Gasification biochar
SGB	Straw gasification biochar
WGB	Wood gasification biochar
AWC	Plant-available water capacity
WHC	Water holding capacity

1. Introduction

An improvement in soil quality and an increase in soil organic matter reduce the exposure and vulnerability of crops to extreme events such as drought (Altieri et al., 2015). The annual soil application of agriculture residues is one of the management tools available for increasing soil organic matter content (Reeves, 1997). However, at the same time the demand for biomass for bioenergy production is growing, putting even more pressure on plant production and the utilization of agriculture and forestry residues (Powlson et al., 2011). Thermal gasification of these residues not only produces sustainable bioenergy (Ahrenfeldt et al., 2013), but also a by-product, gasification biochar (GB), a potentially valuable soil amendment (Müller-Stöver et al., 2012). Depending on the feedstock and specific thermal technology used, GB may contain up to 60% carbon, which has been shown to be stable towards microbial degradation after soil application and may stay in the soil carbon pool for decades (Hansen et al., 2015). Soil application of GB has the potential to increase the soil organic carbon content, thereby having a beneficial impact on climate change mitigation and soil quality (Sohi et al., 2010).

However, very little research has been undertaken so far on the effect of GB soil amendment on physical soil properties and plant growth. The majority of studies available have been conducted with pyrolysis biochar, the main product of a pyrolysis process conducted under low-oxygen conditions at temperatures of between 400-750°C (Kammann et al., 2011; Baronti et al., 2014; Abel et al., 2013). Pyrolysis biochar typically contains 50-80% carbon, often including a labile carbon fraction that can stimulate microbial activity influencing initial mineralization processes (Bruun et al., 2011). On the other hand, GB is produced at higher temperatures (700-1200°C), resulting in a by-product with a lower C content (20–60%) but higher stability towards microbial degradation (Müller-Stöver et al., 2012; Bruun et al., 2014; Hansen et al., 2015).

Biochar has a significant adsorbing ability due to its high specific surface area, and its internal porosity may contribute to increasing the water holding capacity (WHC) (Uzoma et al., 2011; Kammann et al., 2011; Bruun et al., 2014) and plant-available water capacity of soil (AWC) (Abel et al., 2013). Especially coarse sandy soils have poor water and nutrient retention, resulting in a risk of drought in dry periods and nutrient losses in wet periods. Hence, large proportions of hydrophilic micropores (0.2 – 30 µm) in biochar, potentially retaining plant-available water, may have the ability to improve AWC in coarse sandy soils (Hardie et al., 2014). Furthermore, decrease in soil bulk density is often reported after biochar application (Rogovska et al., 2014) along with an increase in total porosity (Abel et al., 2013), which may improve the soil structure, resulting in better water retention (Sun and Lu, 2014) and improved root growth (Bruun et al., 2014). Thus, improvement of AWC in biochar-amended soil is apparently not straightforward, but rather a combination of several factors such as soil type, biochar amendment rate and biochar properties (Barnes et al., 2014). In a vineyard field experiment, Baronti et al. (2014) reported that biochar application increased the available water content and leaf water potential during dry periods. In contrast, Jeffery et al. (2015) found that biochar had no effect on soil water retention, which they attribute to the hydrophobicity of the biochar used. Similarly, Hardie et al. (2014) found that acacia biochar had no effect on plant-available water capacity in a sandy loam soil, partly due to the high natural variation in soil physical properties. Biochar amendment has also shown the ability to increase plant root and shoot growth and drought tolerance without increasing soil water availability, improving plant ecophysiological responses related to water status such as leaf osmotic potential, stomata resistance and water use efficiency (Kammann et al., 2011; Haider et al., 2014).

An improvement in soil structure may be especially beneficial in coarse sandy soils showing high mechanical resistance to root growth due to low compressibility and high friction (Bruun et al., 2014). Rooting depths of only 50-70 cm are reported in soils with coarse sandy subsoil, while in loamy soils located under the same climatic growing conditions roots may reach depths of >140 cm (Madsen, 1985). Consequently, the yield potentials of crops can generally not be fully exploited in coarse sandy soils. However, the particle size and pore structure of the specific biochar material may play a significant role when aiming for soil structure improvement (Abel et al., 2013; Sun and Lu, 2014).

Further information about the effects of specific GBs on the properties of different soil types as well as on plant growth under drought stress is required to learn more about how to optimize the use of a limited amount of GB material to improve soil quality and increase crop yields. The overall aim of this study was therefore to evaluate the effects of two contrasting GB materials on the capacity of plant-available water (AWC) and plant growth responses (shoot and root biomass, leaf water potential, stomatal conductance and carbon isotope discrimination) of spring barley (*Hordeum vulgare* L.) grown in two different soil types under sufficient and reduced water supply.

2. Materials and methods

2.1. Biochar

Two biochar materials were used in this study: wood gasification biochar (WGB) and straw gasification biochar (SGB). SGB was produced in a Low Temperature Circulating Fluidized Bed gasifier (LT-CFB) at 750°C using winter wheat (*Triticum aestivum* L.) as a feedstock. WGB was produced in a TwoStage gasifier at 1200°C from pine wood (*Pinus spp.)* (Ahrenfeldt et al., 2013). A number of physicochemical characteristics were determined for the GB produced and are shown in Table 1 and 2. The total content of organic C was measured on an elemental analyzer (FLASH 2000 Organic Elemental Analyzer, Thermo Scientific, Cambridge UK). The elemental composition was determined by ICP-OES after acid digestion (ISO 11885). The specific surface area was determined by the Brunauer-Emmett-Teller (BET) method by nitrogen gas sorption at 77 K (Quantachrome instruments, Boynton Beach, USA). The pH of the biochar was measured in a 1:5 (w/v) biochar/Milli-Q water suspension by using a pH meter (Mettler-Toledo AG, Switzerland). More details about the production processes, analytical methods and further characteristics of both SGB and WGB can be found in Hansen et al. (2015).

Table 1 here.

Table 2 here.

2.2. Soils

The soils used in this study were sandy loam and sandy soils (USDA textural classification). The sandy loam soil was collected from the Ap horizon (0-25 cm) of a conventional agricultural field on the

Bregentved Estate in Zealand, Denmark (55° 22’ N, 12° 05’ E). The sandy soil was collected on the Jyndevad Research Station of Aarhus University, Denmark (54° 53’ N, 9° 07’ E) from the B horizon (25-100 cm depth) and is further termed coarse sandy soil. Both soils were air-dried and sieved to obtain a fraction ≤ 2 mm. The soil properties are shown in Table 3.

Table 3 here

2.3. Experiment setup

The experiment was conducted in the Risø Environmental Risk Assessment Facility (RERAF) phytotron at the Technical University of Denmark, Roskilde campus, Denmark. The experiment involved 12 treatments with four replicates: two soil types, three GB amendments (control without GB, 1% WGB and 1% SGB respectively) and two water regimes (70% and 30% of the water-holding capacity (WHC) of the control treatment respectively). It was decided to base the water supply on the WHC of the control treatment to avoid effects simply caused by a higher water supply to the biochar-amended pots. The WHC was determined for each soil type in 28 cm-high PVC pots with an inner diameter of 10 cm, equipped with a wick system at the bottom allowing drainage preventing eventual excessive accumulation of water near the lower boundary (Fig. 1). To determine WHC, the sandy loam soil was packed into the pots using pressure of a metal piston of the same diameter as the pot, which resulted in a bulk density of 1.47 g cm^{-3} in the control treatment. The coarse sandy soil was added to the pot without pressure and had a bulk density of 1.63 g cm^{-3} in the control treatment. The pots with soil were submersed in water for 24 hours following a subsequent drainage period of 24 hours while preventing evaporation. The recorded weight of the water held in the soil after drainage was taken as WHC.

Prior to the experiment, the dry soil was weighed into plastic bags to give 2.6 kg of sandy loam soil and 3 kg of coarse sandy soil respectively. Nutrients were added in a liquid solution to the soil in each bag at a rate of 60 mg P, 40 mg Mg, 124 mg S, 166 mg K, 3.4 mg Mn, 1.2 mg Zn, 0.2 mg Cu and 0.1 mg Mo kg^{-1} soil (as KH_2PO_4, $MgSO_4$, K_2SO_4, $MnSO_4$, $ZnSO_4$, $CuSO_4$, Na_2MoO_4). The soil was thoroughly mixed with 1% of the GB material on a dry weight basis. The WGB was sieved to obtain a fraction < 1 cm. The mixtures and control treatments were packed with the same pressure as for the WHC determination, respectively. With these densities, 1% of GB corresponds to approximately 36 t ha^{-1} in a sandy loam soil and approximately 40 t ha^{-1} in a coarse sandy soil, if incorporated to 25 cm soil depth.

Prior to the experiment, the conditions in the phytotron were set as follows: The daylight period was set to 16 hours and the environmental parameters were controlled as follows (day/night): temperature (22/16°C), photosynthetically active radiation (400/0 µmol $m^{-2}s^{-1}$) and relative air humidity (55/70%). All the pots were watered from the top to 80% of the WHC of the control treatments during the first week of the experiment to avoid dry soil at the bottom of the pots. All pots received 100 mg N kg^{-1} soil in a liquid solution after irrigation before sowing and the same amount 21 days after sowing. After one week, five spring barley (*Hordeum vulgare* L., cv. Quench) seeds were sown at approximately 1 cm depth and two water regimes were established by watering the pots to 30% and 70% of control treatment WHC, respectively. However, treatments under the 30% water regime were watered to reach 50% WHC of the control up to 10 days after sowing to secure germination, whereupon 30% WHC was maintained for the rest of the experiment. Plants were thinned to three plants per pot and supported with wooden plant sticks to avoid lodging. Each pot received 50 g plastic beads on the top of the soil to minimize soil water evaporation. The pots were watered to weight from above every second or third day during the first weeks and daily during the final week of the experiment. No drainage from the pots was observed during the experiment. Cumulative water consumption was calculated from the day on which all the plants had been germinated until the day of harvest as the sum of water loss from each treatment recorded at each watering time

Fig. 1 here

2.4. Plant ecophysiological measurements and yield

Stomatal conductance was used as an indicator of plant drought stress, as plants close stomata to reduce water loss and consequently stomatal conductance decreases. Stomatal conductance measurements using a leaf porometer SC-1 model (Decagon Devices) was initiated 25 days after sowing and was conducted two hours after the light had been switched on. Measurements were performed on the upper surface of the youngest fully emerged leaf, approximately 5 cm from the stem. Three measurements per pot were taken.

Leaf water potential was used as an indicator of soil water availability. The leaf water potential was measured 37 days after sowing in a pressure chamber using the digital plant moisture system Skye SKPM 1400 connected to pressurized air (Skye Instruments Ltd., United Kingdom) on the first two fully expanded leaves per pot. The measurements were performed as “pre-dawn measurements” during the night, three hours after nightfall, which was approximately 20 hours after the last watering, and then continued for four hours.

The plants were harvested six weeks after sowing by cutting the aboveground plants by hand just above the soil surface. The roots were isolated by gently pressing the soil out of the pot, followed by carefully rinsing the roots with water. Both shoots and roots were dried in an oven for 48 hours at 70°C and their dry weight determined.

Carbon isotope discrimination was used as an indicator of water use efficiency. Carbon isotope discrimination was analyzed on the harvested aboveground dried plants. Plant samples were first coarsely ground in a plant mill to pass a 4 mm sieve and secondly finely ground in a ball mill and weighed into tin capsules. The carbon isotope composition was determined on an elemental analyzer (FLASH 2000 Organic Elemental Analyzer, Thermo Scientific, Cambridge, UK) coupled to an isotope ratio mass spectrometer using the Vienna PeeDeeBelemnite as a standard. The carbon isotope discrimination (Δ) was calculated as:

$$\Delta\ (‰) = \left[\frac{(\delta_{air} - \delta_{plant})}{(1 + \delta_{plant})}\right] * 1000 \text{ (Equation 1)}$$

where δ_{air} was assumed to be -0.008 (Farquhar et al., 1989).

2.5. Soil measurements

Soil pH was only measured on soil samples from the 70% WHC treatments, using a soil-water suspension of 5 g soil and 25 ml of Milli-Q water (pH meter Mettler-Toledo AG, Switzerland), assuming no pH effects of the water regimes.

Pots under the 30% WHC water regime were used to determine water retention, as the root growth in those pots was lower compared to the pots under 70% WHC. This made it possible to take soil samples from the bottom of the pots with less root content. Undisturbed soil samples were taken after harvest in a metal ring of 100 cm^3. The ring was pressed into the soil from the bottom end of the pot. The soil content of the pot was carefully pushed out of the pot in order to minimize disturbance when cutting the intact ring with soil. The samples were saturated by adding de-aired water from the bottom end and leaving the samples at zero tension for 24 hours. Moisture retention was determined at suctions of 50 cm (for coarse sand) or 100 cm (for sandy loam) using a tension table with a hanging water column, and at 15.5 bars suction (both soil types) using a suitable pressure plate extractor and pressure chamber (Dane and Hopmans, 2002). These suction levels were chosen to represent field capacity (pF 1.7 in coarse sand and 2.0 in sandy loam) and permanent wilting point (permanent wilting point at pF 4.2). The samples were left for 72 hours at 50 and 100 cm tension, and for 21 days at pF 4.2 to reach equilibrium. The measurements were performed in quadruplicate per treatment, *i.e.* per combination of soil type and GB level.

Moisture content at equilibrium (m_w, g) was obtained as the difference between the masses of moist and oven-dried soil (105°C). The volumetric moisture content (θ, cm^3 cm^{-3}) of the ring samples (*i.e.* at field capacity) was calculated as water volume divided by sample volume (100 cm^3) using a water density of ρ_w=1.00 g cm^{-3}. Dry bulk density was calculated from ring samples as the ratio of oven dry mass (m_{sd}, g) to sample size (100 cm^3). The volumetric water content at pF=4.2 ($\theta_{4.2}$, cm^3 cm^{-3}) was calculated as:

$$\theta_{4.2} = w\frac{\rho_b}{\rho_w} \quad \text{(Equation 2)}$$

where w is the gravimetric moisture content ($w=m_w/m_{sd}$) and ρ_b is the average dry bulk density measured on ring samples for the same treatment.

The plant AWC was calculated as the difference between volumetric water content at field capacity and permanent wilting point.

2.6. Statistical analysis

Statistical analysis of the data was performed in R, version 0.98.1103. The significant interaction effect of the soil type, water regime and GB addition was assessed using a three-way analysis of variance (ANOVA). The effect of the water regime within each soil type was analyzed by two-way ANOVA. The differences between treatments within each soil type and water regime were analyzed using least-square means from the R-package lsmeans (Lenth and Herv, 2015). P values were adjusted using the Tukey method. All differences at $P < 0.05$ were reported as significant. Prior to analysis, data were tested for homogeneity of variance and normality of residuals using the Wally plot (R MESS package) and log or square root transformed if necessary.

3. Results

3.1. Shoot and root growth

Shoot and root growth was affected by soil type, water regime and GB addition and type (Fig. 2). The results from ANOVA analysis of single and interaction effects are shown in Table 4. Shoot and root growth was lower when barley was grown in coarse sandy soil compared to the sandy loam (p = 0.0001). In the sandy loam, the 30% WHC regime had a significantly negative impact on both shoot and root growth (p < 0.0001). Neither SGB nor WGB addition had any effect on root growth under either water regime, while shoot growth decreased by the WGB addition under the 70% WHC regime. In the coarse sandy soil, the 30% WHC regime had no effect on shoot or root growth in the control treatments compared to the 70% WHC regime. The addition of SGB to the coarse sandy soil increased shoot growth by 165% and root growth by 50% under the 70% WHC regime; however the shoot biomass was still only half of the biomass obtained in the sandy loam soil. Under the 30% WHC regime, the addition of SGB increased shoot growth by 40% and root growth by 57%. In contrast, the addition of WGB to coarse sandy soil had no effect on shoot growth under 70% WHC, a negative effect on shoot growth under 30% WHC, and no effect on root growth under either water regime.

Fig. 2 here

Table 4 here

3.2. Plant ecophysiological responses

Generally the water regime had an effect on the plant ecophysiological responses, while the addition of GB had variable effects (Table 4). The stomatal conductance of barley leaves decreased significantly under the 30% WHC regime compared to the 70% WHC regime in both soil types ($p < 0.001$, Table 4). In the sandy loam soil, stomatal conductance decreased when amended with WGB under the 70% WHC regime compared to the control, while there was no effect of GB addition under the 30% WHC regime. In the coarse sandy soil, the application of WGB significantly decreased stomatal conductance under 30% WHC, whereas there was no effect of GB under the 70% WHC. The leaf water potential of barley leaves varied and was not significantly affected either by the water regimes or by GB addition (data not shown).

The carbon isotope discrimination was highest under the 70% WHC regime and decreased significantly under the 30% WHC regime in both soil types ($p < 0.0001$) (Fig. 3 c,d), confirming the stomatal conductance measurements. GB amendments had no effect on carbon isotope discrimination (Table 4).

The cumulative water consumption of barley plants overall corresponded to plant growth (Fig. 2, 4). In the sandy loam soil, cumulative water consumption was affected by the water regime but not by GB addition, being highest under the 70% WHC regime (Fig. 4). In contrast, in the coarse sandy soil it was affected by both water regime and GB addition. SGB addition increased cumulative water consumption in the 70% WHC regime, while the addition of WGB decreased it under both water regimes.

Fig. 3 and 4 here.

3.3. Soil measurements

The application of GB did not have any effect on bulk density in either of soil types (data not shown). Both soil type and GB addition affected field capacity, permanent wilting point and AWC (Fig. 5), that were generally higher in the sandy loam soil compared to the coarse sand. The addition of WGB increased the permanent wilting point by 9% in sandy loam and 43% in coarse sand, while the SGB addition had no effect. The field capacity and AWC were increased by both GB types in both soil types, although the effect was highest in the coarse sandy soil treatments. The AWC was increased by 18% in SGB and 17% in WGB treatment in sandy loam, while it was increased by 42% in SGB and 31% in WGB treatment in coarse sand. The addition of both GBs increased the pH of the coarse sandy soil (Fig. 6). The application of WGB had the highest impact and increased the pH from 6.2 to 8.3. In the sandy loam soil, pH was only increased by WGB application.

Fig 5 and 6 here

4. Discussion

4.1. Effect of reduced water supply on plants

The reduced water supply affected root and shoot growth and plant water consumption in the sandy loam soil considerably, while in the coarse sandy soil the differences between the two water regimes were generally less pronounced. Plant growth in the control treatments in coarse sand was approximately the same under both water regimes. This may be due to the fact that coarse sandy soil under 30% WHC is not as close to the wilting point as sandy loam. However, the main reason is most likely the limited root growth caused by mechanical resistance, which often occurs even under moderately wet conditions (Whalley et al., 2006; Bengough et al., 2011). The reason for this is the high soil strength of sandy particles, as greater pressure is required to push the particles aside so that the root can penetrate (Barber, 1995). The applied additional water may have accumulated in the bottom of the pot with fewer roots and was therefore not fully available for root uptake. Accordingly, the negative effects of the reduced water regime on stomatal conductance and carbon isotope discrimination in coarse sand were limited and not significantly different from the 70% WHC treatment. In contrast, in the sandy loam stomatal conductance and carbon isotope discrimination decreased significantly under the 30% WHC treatments as a consequence of plant water stress, which is in accordance with other studies (Kammann et al., 2011; Kottmann et al., 2014). The exposure of plants to drought stress typically also decreases leaf water potential (Farooq et al., 2009). However, this was not observed in the current study, probably because the leaf water potential was sampled pre-dawn and therefore the plants can compensate with a continuous water uptake during nighttime in contrast to stomatal conductance that was measured during daytime (Schulze et al., 1985).

4.2. The effect of SGB in sandy loam soil

In the sandy loam soil, the addition of SGB increased water content at field capacity and AWC. In other investigations, the effects of biochar on the hydraulic properties of loamy soils are reported to vary. Several studies showed positive effects of biochar amendment to loamy sand and sandy loam soils on field capacity and AWC (Abel et al., 2013; Peake et al., 2014), while no effects of biochar amendment on field capacity and permanent wilting point were observed in a study by Hardie et al. (2013). The varying effects are caused by the interaction of many factors such as soil texture, soil organic matter content, physicochemical biochar characteristics and biochar application rate. For instance, Abel et al. (2013) observed the greatest increase in AWC by biochar application in sandy soils and no effect on soils with high organic matter content. In this study, the GB-induced increase in field capacity and AWC was not expected to lead to an increase in shoot and root growth, as all treatments were kept at either 30% or 70% WHC of the control soil. Hence, the GB-amended soils did not receive higher amounts of irrigation water compared to the control soils. However, a beneficial effect of increased AWC by GB on plant growth can be expected under field conditions, *e.g.* in the case of thorough wetting followed by subsequent drought. The addition of SGB did not have any other positive effects on shoot or root growth in the sandy loam soil under 70% WHC, which is probably due to the soil's moderate clay and SOM content and a soil texture that enables root development for sufficient water uptake to support plant growth. However, no positive effects of SGB on plant growth under drought stress were observed either.

4.3. The effect of SGB in coarse sandy soil

In the coarse sandy soil, SGB increased water content at field capacity and AWC as well, which has also been documented in other studies on coarse sandy soils (Uzoma et al., 2011; Abel et al., 2013; Barnes et al., 2014). The addition of SGB resulted in considerably increased root and shoot growth under both water regimes. Similar results were obtained by Kammann et al. (2011), where biochar application to poor sandy soil increased the shoot and root growth of quinoa. In addition, the authors reported an improvement in plant water status after the application of biochar when the same limited amount of water was applied to all treatments. This contrasts with the present study where plant physiological responses did not differ from the control treatments, even when biomass production was significantly increased. We cannot completely exclude that the positive impact on plant growth was caused by the addition of plant nutrients - such as K - to the nutrient-poor sandy soil, although it was intended to avoid fertilizer effects by adding sufficient nutrients to all treatments. However, the addition of mineral nutrients in WGB did not show any benefits, therefore we assume that the great positive effect of SGB on plant biomass in coarse sand was most likely due to reduced mechanical impedance to root growth. The importance of the soil structure can be corroborated by the fact that in contrast to the sandy loam, the 70% water regime did not have a positive effect on the plants in the coarse sandy soil in the non-amended control treatments, as discussed in section 4.1. We hypothesize that when adding SGB to sandy soil, some of its small particles may settle between the coarse sand particles, thereby reducing friction, whereas others may transform large drainable pores into smaller pores. Smaller pores can improve the water supply by increasing the AWC and contact between the roots and the water. This is consistent with the findings of Bruun et al. (2014), who reported that SGB increased water retention in coarse sandy soil and improved root growth of barley, increasing the grain yield by 22%.

Under field conditions, the increased AWC and improved root growth may lead to improvements in both water and nutrient retention and hence decrease the leaching of mobile nutrients, such as nitrate (Sika and Hardie, 2014). Improving the quality of coarse sandy soils has global potential, since the lack of yield potential utilization caused by limited AWC and poor root development affects agricultural production in many regions of the world, for example in parts of Africa dominated by poor sandy soils (Sika and Hardie, 2014) or areas in Denmark dominated by coarse sandy subsoils (Bruun et al., 2014). However, the underlying mechanisms for improving the soil structure of coarse sandy soil by SGB need further investigation.

4.4. The effect of WGB

WGB increased water content at field capacity and AWC to the same extent as SGB, but no positive effect on plant growth could be observed after the application of WGB in any of the soils or treatments. Quite the opposite, in fact, since WGB even decreased shoot growth under the 30% WHC water regime compared to the control in the coarse sandy soil. The lack of a positive effect of WGB in this soil might be due to its higher proportion of larger particles (53% larger than 0.125 mm) compared to SGB. Due to fewer but larger particles heterogeneously distributed in the soil, WGB may not be able to change the skeleton of the soil matrix and increase the water retaining pore space volume to the same degree as SGB. It may also be difficult for the roots to utilize water retained by large particles of WGB. In fact, WGB addition increased the water retention at permanent wilting point, indicating that WGB binds more water that is then non-available to plants. This is most likely due to the high SSA and thus increased microporosity of WGB (Abel et al., 2013) and may be a reason for the reduced shoot and root growth and stomatal conductance under the 30% WHC water regime in coarse sandy soil. However, as the WGB addition also resulted in decreased stomatal conductance and a reduction in plant biomass under the 70% WHC treatment in the sandy loam soil without a decrease in water consumption, we cannot exclude other detrimental effects of this material on plant growth. The WGB was most efficient at increasing soil pH. Although potentially beneficial for soil fertility and crop production in acidic soils (Deal et al., 2012), this may reduce the availability of certain nutrients in already alkaline soils. However, since pH was not significantly different in either GB-amended treatment in the sandy loam, it seems unlikely that increased soil pH was the only reason for reduced plant growth in the WGB treatment.

5. Conclusions

The reduced water regime significantly affected plant ecophysiological responses, plant growth and water consumption in the sandy loam soil, whereas it only had a small or no effect in the coarse sandy soil. Both gasification biochars increased the plant-available water content in both the sandy loam and the coarse sandy soil. However, the two contrasting GB materials had different effects on plant growth in the two soil types tested, suggesting that the mitigation of specific soil restraints needs specifically adapted GB materials. The application of WGB had either no effect or slightly negative effects on plant ecophysiological responses and growth. Under which conditions WGB with its interesting properties such as high SSA, pH and porosity can positively affect plant growth has to be the subject of future research. The greatest benefits were observed on coarse sandy soil where SGB markedly increased root and shoot growth under both water regimes. These results suggest that there is great potential in the ability of SGB to increase soil pH, water retention and root development in order to improve crop productivity on the often poor coarse sandy soils in many parts of the world. However, the results of this study are based on a pot experiment with disturbed soil and need to be verified in field experiments.

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Table 1 Chemical characterization and particle size distribution of the SGB (straw gasification biochar) and WGB (wood gasification biochar) materials (modified from Hansen et al. 2015)

Parameter	Unit	SGB	WGB
C	g kg^{-1}	468	653
P	g kg^{-1}	4	3.4
K	g kg^{-1}	72	25
S	g kg^{-1}	1.2	0.17
Mg	g kg^{-1}	4.6	5.9
Ca	g kg^{-1}	18	52
Fe	g kg^{-1}	1.7	16
Zn	mg kg^{-1}	64	160
Cu	mg kg^{-1}	13	55
pH (water)		11.6	11.1
Particle size distribution	% of dry mass		
< 0.045	mm	89.3	33
0.045-0.125	mm	10.3	13.7
>0.125	mm	0.3	53.3

Table 2 Brunauer–Emmett–Teller (BET) specific surface area (SSA) and pore volume of straw gasification biochar (SGB) and wood gasification biochar (WGB). WGB was divided into two size fractions (modified from Hansen et al. 2015)

Biochar	Particle size (mm)	SSA (m^2 g^{-1})	Pore volume (cm^3 g^{-1})
SGB	0-1	75	0.04
WGB	0-0.5	426	0.52
WGB	0.5-1	1027	0.58

Table 3 Soil texture, pH, soil organic matter (SOM) and soil water-holding capacity (WHC)

	Clay %	Silt %	Fine sand %	Coarse sand %	pH (water)	SOM %	WHC %
Sandy loam	14	14	47	24	7.9	3.4	29
Coarse sand	2.3	0.9	18.9	77.9	6.8	0.3	19

Table 4 Results from three-way anova of single and interactions effects of soil type (Soil), gasification biochar (GB), water regime (WR) on shoot and root growth of spring barley, stomatal conductance (SC) and carbon isotope discrimination (CID)

Factors	**Shoots**		**Roots**		**SC**		**CID**	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Soil	676.9	<0.001	44.5	<0.001	1.1	N.S.	0.2	N.S.
GB	52.4	<0.001	3.2	0.05	4.9	0.01	1.1	N.S.
WR	503.8	<0.001	33.1	<0.001	101.8	<0.001	148.5	<0.001
Soil x GB	14.9	<0.001	1.9	N.S.	1.7	N.S.	0.5	N.S.
Soil x WR	274.5	<0.001	25.7	<0.001	4.4	0.04	32.1	<0.001
GB x WR	11.2	<0.001	1.7	N.S.	2.8	N.S.	0.6	N.S.
Soil x GB x WR	3.2	0.05	1.5	N.S.	8.1	0.001	0.7	N.S.

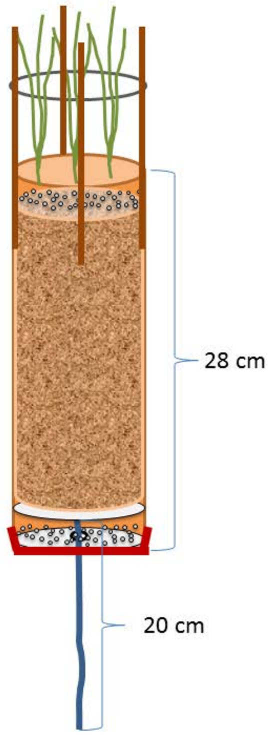

Fig. 1 The experimental setup of pots with a drainage system consisting of two layers of felted fabric in the bottom with a 1 cm-thick layer of 5 mm plastic beads in between, and a 20 cm-long cotton wick, attached to the inner felted fabric, passing through those layers

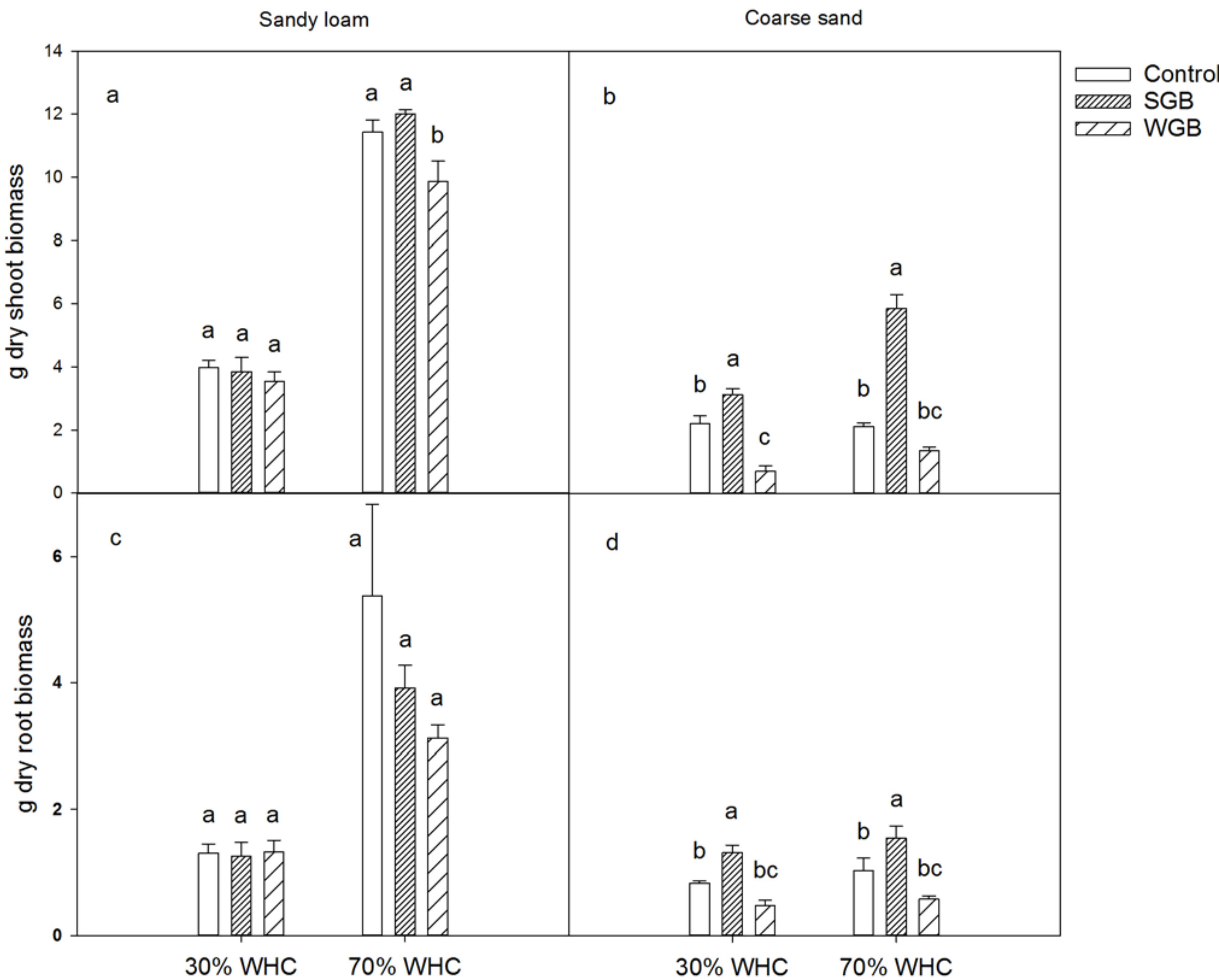

Fig. 2 Dry shoot biomass (g) of spring barley per pot after 6 weeks of the experimental period (a,b) and dry root biomass (c,d) on sandy loam soil (a,c) and coarse sandy soil (b,d) grown under two water regimes: 30% and 70% of the water-holding capacity (WHC) of the control treatment respectively. Control = non-amended soil, SGB = soil with 1% straw gasification biochar and WGB = soil with 1% wood gasification biochar. Values presented are means with standard error bars (n=4). Different letters indicate significant differences between treatments within each water regime (P < 0.05)

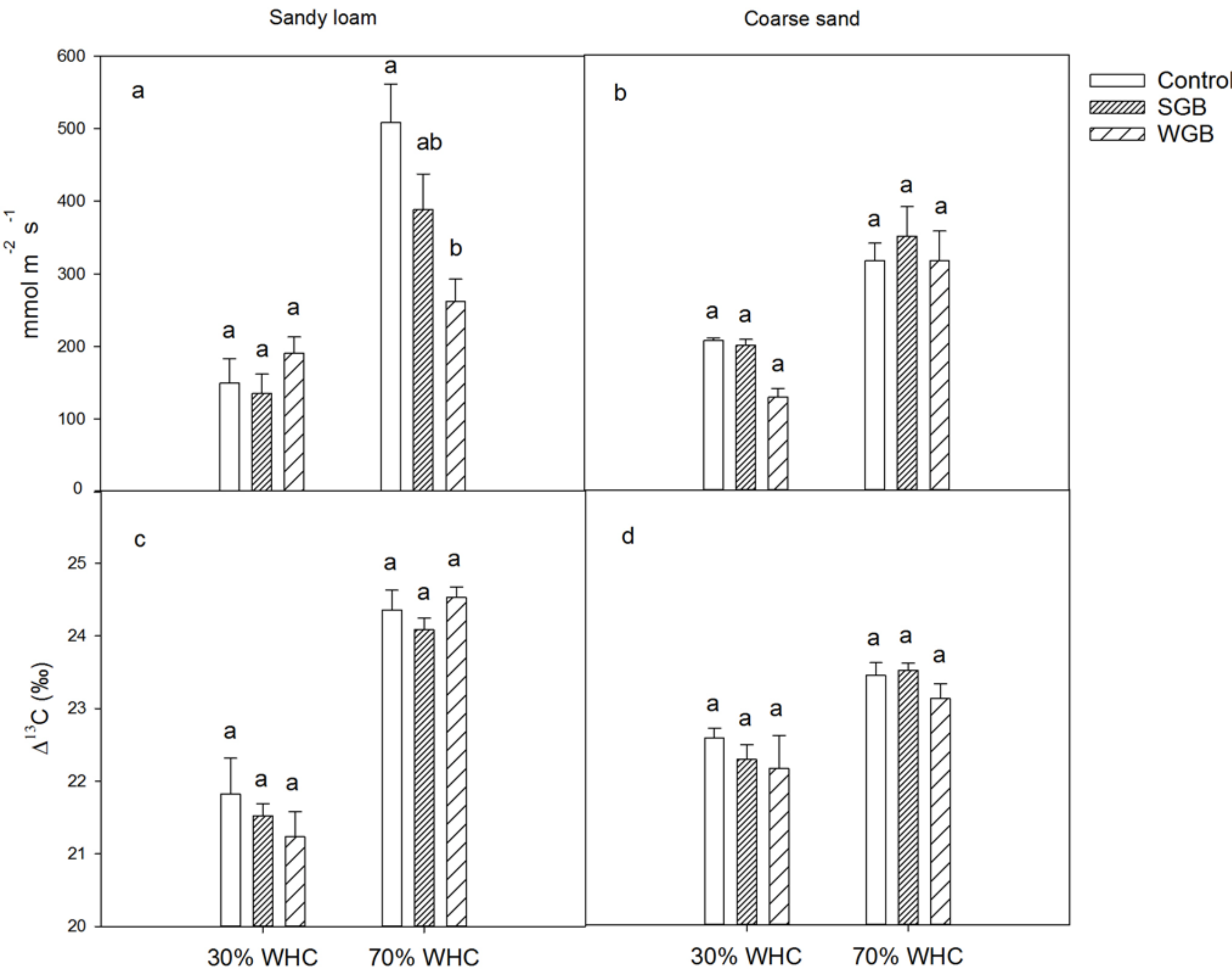

Fig. 3 Stomatal conductance of barley leaves (a,b) and carbon isotope discrimination in plant tissue (c,d) on sandy loam soil (a,c) and coarse sandy soil (b,d) measured under two water regimes. For treatment abbreviations, see Fig. 2. Values presented are means with standard error bars (n=4 for stomatal conductance and n=3 for carbon isotope discrimination). Different letters indicate significant differences between treatments within each water regime ($P < 0.05$)

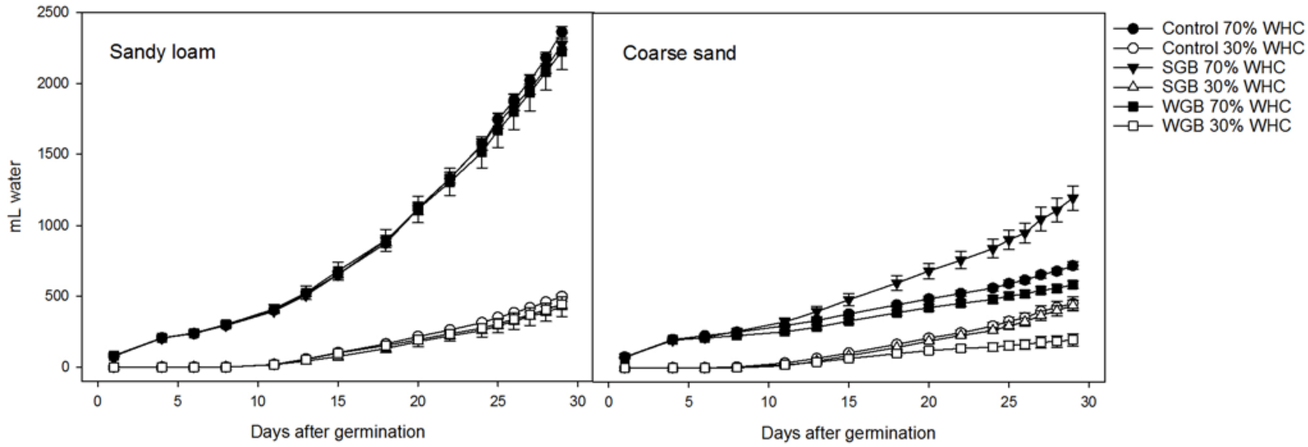

Fig. 4 Cumulative plant water consumption (mL water pot^{-1}) from germination until harvest in all treatments in sandy loam and coarse sandy soil respectively. For treatment abbreviations, see Fig. 2. Values presented are means with standard error bars (n=4)

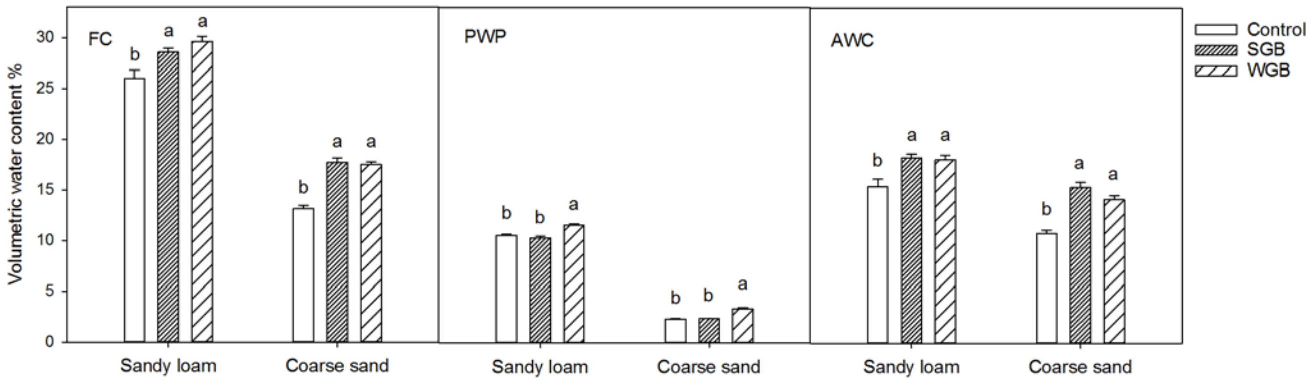

Fig. 5 Field capacity (FC), permanent wilting point (PWP) and available water content (AWC) measured at the end of the experimental period. For treatment abbreviations, see Fig. 2. Values presented are means with standard error bars (n=4). Different letters indicate significant differences between treatments within each soil type (P < 0.05)

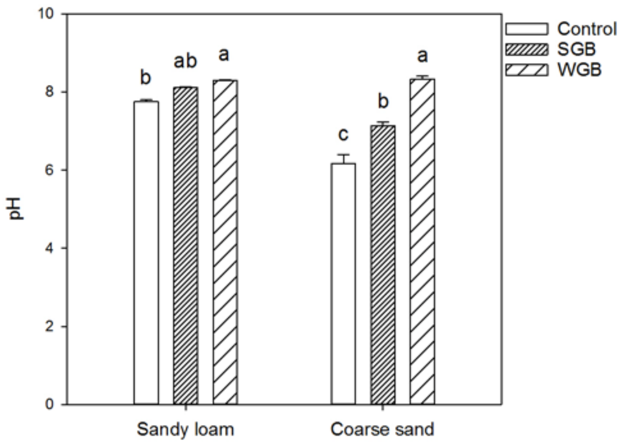

Fig. 6 Soil pH measured at the end of the experimental period. For treatment abbreviations, see Fig. 2. Values presented are means with standard error bars (n=3). Different letters indicate significant differences between treatments within soil type (P < 0.05)